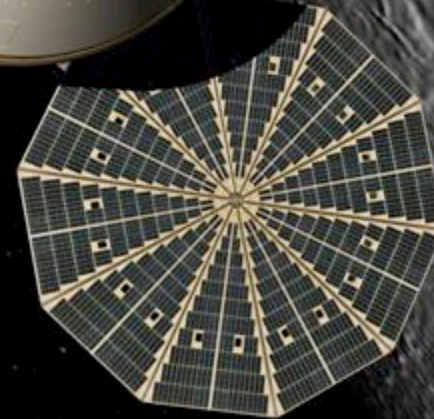
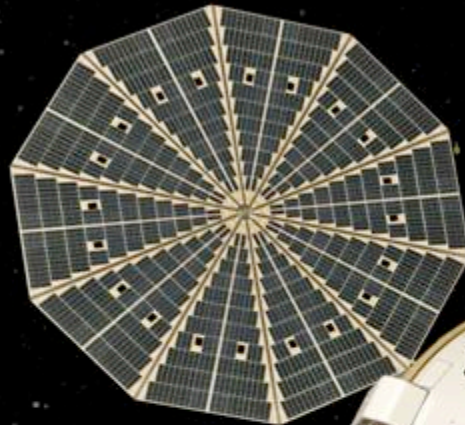




CONSTELLATION



Orion Thermal Protection System, Advanced Development Project

***7th International Planetary Probe Workshop,
June 16th, 2010***

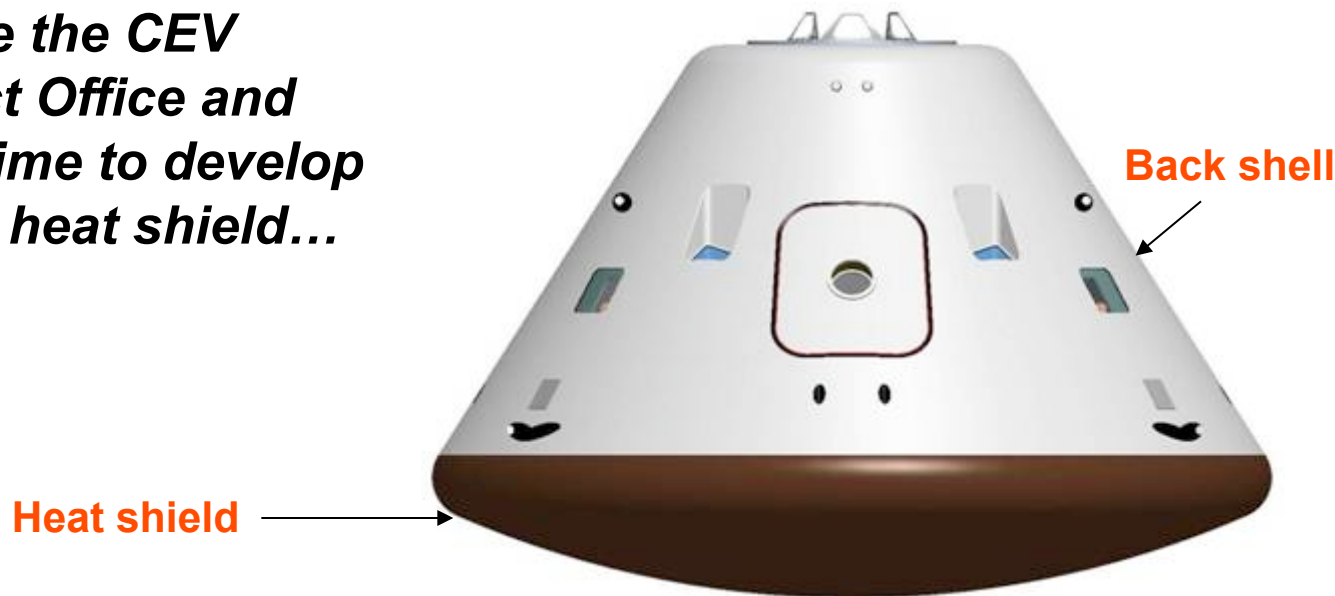
***James Reuther
National Aeronautics & Space Administration
Ames Research Center***



The Orion TPS Objective



Enable the CEV Project Office and the Prime to develop a CEV heat shield...



Orion Lunar direct return (LDR) conditions:

- 11 km/s atmospheric entry
- peak heat rate $> 750 \text{ W/cm}^2$

Orion Low Earth Orbit (LEO) return conditions:

- 7.5 km/s atmospheric entry
- peak heat rate $> 150 \text{ W/cm}^2$

... by initiating an Advanced Development Project to raise the TRL and reduce the risk of Lunar return capable ablative TPS materials and heat shield systems



Background



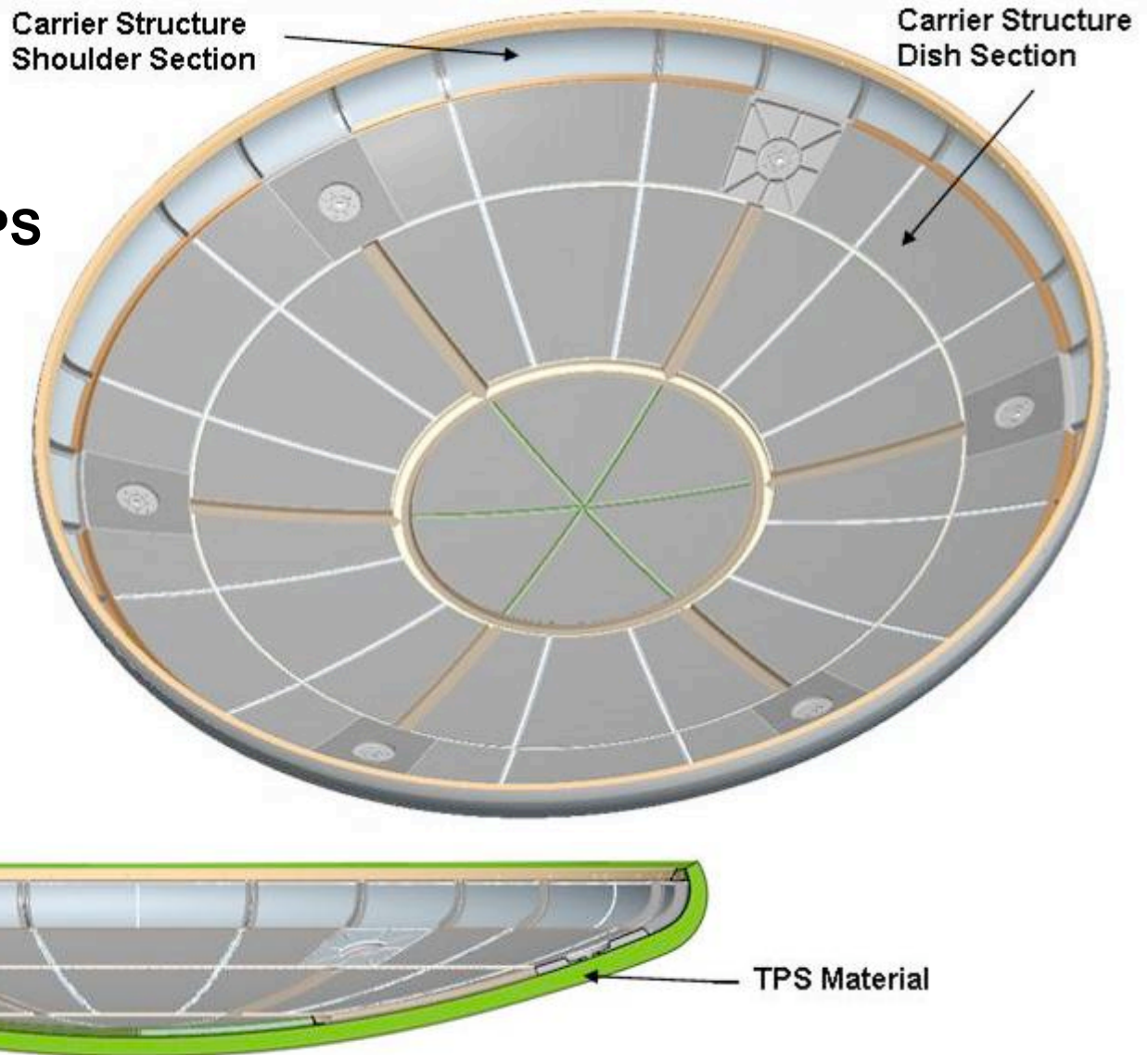
- **The Exploration Systems Architecture Study (ESAS) commissioned in the summer of 2005 settled on a new Constellation (Cx) human space transportation architecture.**
- **The ESAS recommended architecture included a new Crew Exploration Vehicle (CEV – Orion) that would serve as the US human transportation system for Low Earth Orbit (LEO) as well as lunar missions**
- **A top risk identified by ESAS was the development of a heat shield and applicable Thermal Protection System (TPS) materials meeting both LEO and Lunar return requirements**
 - Ablative TPS materials required to support LEO and Lunar missions
 - The US had focused little attention on ablative materials since Apollo era
 - All applicable ablative TPS materials were at low technology readiness levels (TRL ~ 3-4)
- **In Oct 2005, the CEV Project commissioned the CEV TPS Advanced Development Project to address the heat shield development risk**



Orion Heat Shield Components



- **Carrier structure**
 - Dish section
 - Shoulder section
- **Ablative acreage TPS**
 - Block layout
 - TPS material thickness
- **Compression pads**
- **Separation mechanism**
- **Main seal**





Scope of TPS ADP Primary Objectives



- **TPS materials fabrication and characterization**
 - Development of material constituent, processing and properties specifications
 - Detailed mechanical and thermal material properties testing
- **TPS materials thermal performance capabilities for LEO & Lunar returns**
 - Nominal & emergency entry trajectories – Aerothermal environments
 - Screening and comprehensive TPS materials thermal performance testing
 - TPS materials thermal response models
 - TPS thermal performance margins policy
- **TPS materials thermal-mechanical performance capabilities**
 - Ground, launch, on-orbit, nominal and emergency entry, descent & landing loads
 - Thermal-structural integrated (carrier structure + TPS) testing
 - FEM analysis and design of TPS materials
- **Design for all heat shield components**
 - TPS acreage, carrier-structure, TPS bonding, compression pads, main seals, gap/seams, close-outs, repairs
- **Integrated heat shield design and performance capabilities**
 - Integrated design of all components
 - TPS material thermal, MMOD and integrated sizing + smoothing and lofting
 - Integrated thermal-structural analysis and design of complete heat shield
- **Manufacturing for an integrated 5 meter heat shield**
 - Infrastructure and equipment for full-scale heat shield production (e.g. full scale oven)
 - Production staffing and resources to produce materials meeting spec. at volume
 - Demonstration of full-scale heat shield manufacturing procedures



Other TPS ADP Objectives



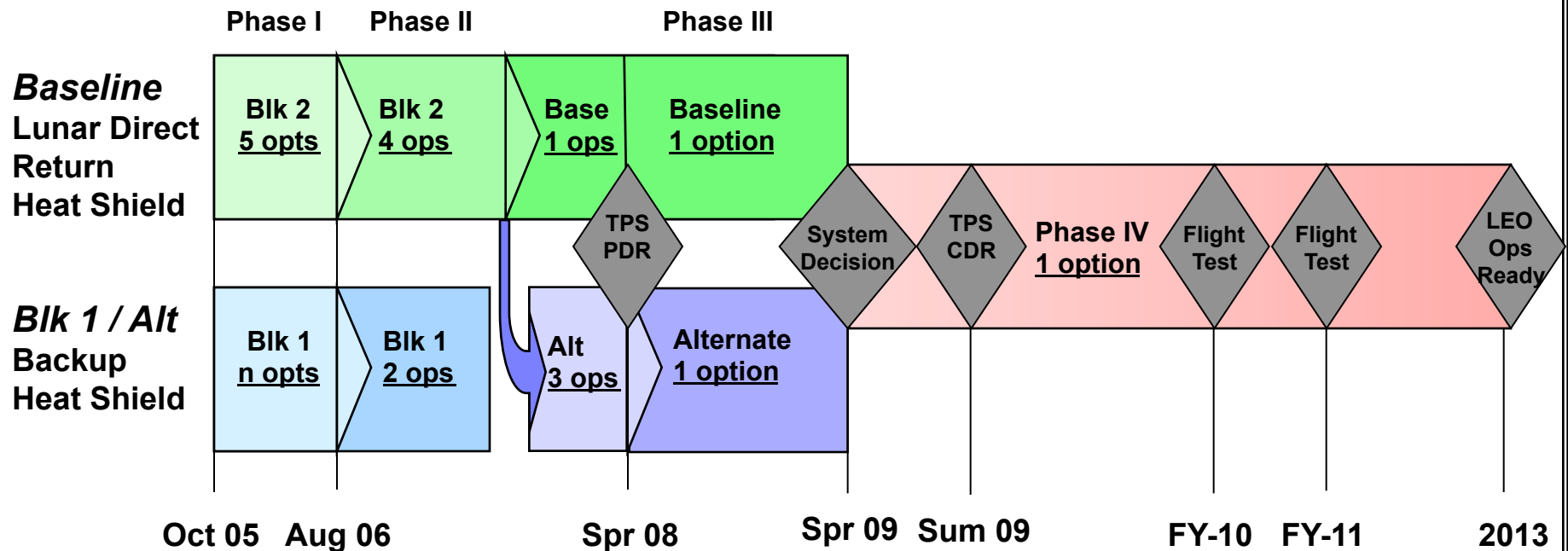
- **Revitalize the ablative TPS industry:**
 - For the past 25+ years, NASA-sponsored R&D has focused mostly on reusable TPS materials
 - Ceramic tiles, coatings, blankets (e.g., Shuttle acreage)
 - Oxidation-resistant carbon-carbon (e.g., shuttle WLE)
 - Ultra High Temperature Ceramics (UHTCs)
 - Little work completed on advanced ablative materials, as a consequence, the ablative TPS materials community in the U.S. (very robust in the 60s and 70s) has significantly diminished
 - NASA is really the only customer for this industry – thus it is vital for NASA to make investments not only internally but also in industry
- **Train the next generation of NASA entry systems developers**
 - Prior to the CEV development, NASA efforts were focused on either basic TPS materials R&D or performing TPS operational support
 - Limited efforts were applied to perform end-to-end development of a new heat shield systems for flight vehicles
 - NASA in house staffing lacked training to perform flight hardware development



CEV TPS Development Strategy (Critical Path Item)



- **Baseline** Heat shield (Lunar and LEO return capable) by Orion IOC → 2014
- **Alternate** Heat shield (Lunar and LEO return capable) parallel development, maintained up through system decision (between Orion PDR and CDR)
- NASA develops **Baseline & Alternate** heat shield designs up to Orion PDR
- Prime takes over responsibility of heat shields after CEV PDR – w/ NASA oversight
- Back shell TPS development controlled by Orion Prime – w/ NASA oversight
- Possible flight test program beginning in 2014 to validate analysis and ground-based testing





Heat Shield Materials



- **Block 2 TPS Materials**

Critical Path for CEV

No longer considered for CEV

- **Textron: Avcoat**
- Boeing / FMI: PICA (Alternate)
- Textron: 3DQP
- Boeing: BPA
- ARA: PhenCarb 28
- Lockheed Martin / CCAT: Advanced Carbon-Carbon / Calcarb

- **Block 1 TPS Materials**

- Lockheed Martin: SLA-561V
- Shuttle tile materials: LI-2200, BRI-18

- **Carrier Structure**

- **Titanium / Titanium honeycomb**
- GR-BMI Composite / Titanium honeycomb (Alternate)







- **Compression Pads**

- **Carbon phenolic**
- Silica phenolic (Alternate)
- Fiberglass phenolic



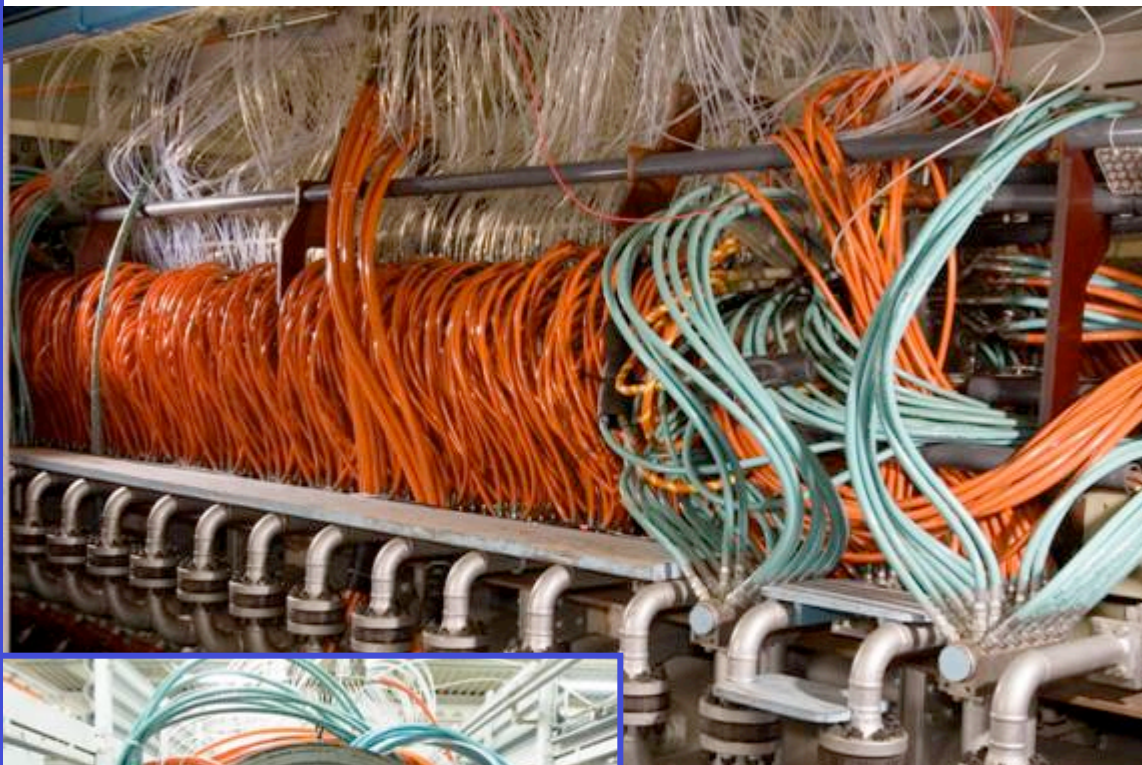
Candidate Heatshield Ablator Materials for Lunar Return (Block 2) Conditions



Vender Material	Heritage Mission & Diameter	Local TPS Approach TTT	System Construction IP	TPS ADP Contracts Density	Image
ARA PhenCarb 28	MDU, TRL = 4 (2007) 1 m	Uniform TTT – in Honeycomb	Segmented with seams	Phase I 450 kg/m ³	
Boeing / FMI PICA	Stardust, TRL = 4 (2006) 0.9 m	Uniform TTT bonded with RTV/SIP/RTV	Blocks/Tiles w/ filled gaps/ seams	Phase I, Phase II 270 kg/m ³	
LM / LCAT ACC / CalCarb	Genesis, TRL = 4 (2004) 1.35 m	Dual layer system	Monolithic or segmented	Phase I 1500 / 180 kg/m ³	
Textron Avcoat	AS-501, TRL = 4 (1967) 3.9 m	Uniform TTT – in Honeycomb	Monolithic w/ honeycomb seams	Phase I, Phase II 540 kg/m ³	
Textron 3DQP	DoD ?, TRL = 3 (?) ?	Dual layer with integration layer	Segmented w/ tongue & groove	Phase I, Phase II 1600 / 220 kg/m ³	
Boeing BPA	Coupons, TRL= 3 (2005) 1 m	Uniform TTT – in Honeycomb	Monolithic or segmented	Phase II 540 kg /m ³	



Block 2, Phase I Testing in Arcjet



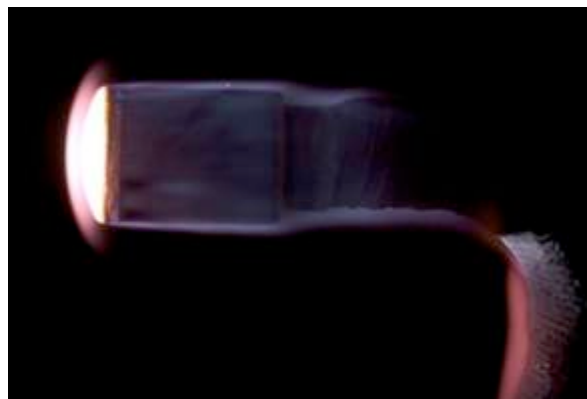
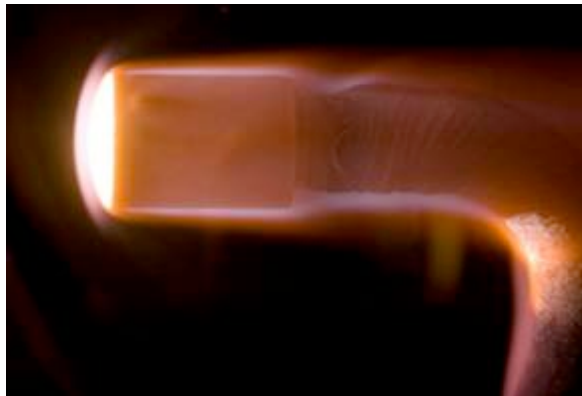
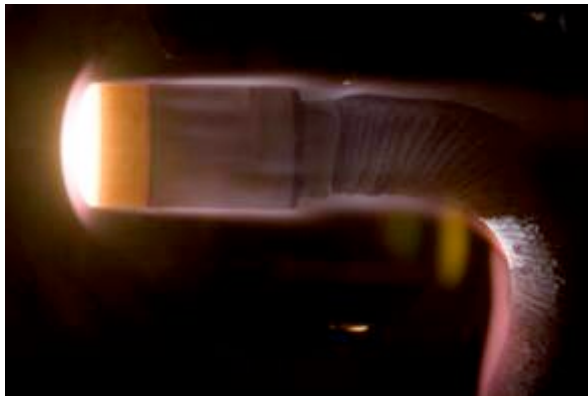


Block 2 Phase I Stagnation Arcjet Testing



Three arcjet test series were performed

- Block 2 peak heating - 1000 W/cm² @ 30 sec --- Ames IHF
- Block 2 skip dual-pulse 400 / 150 W/cm² --- Ames AHF
- Block 1 nominal entry – 130 W/cm² @ 200 sec --- Ames IHF





Block 1 SLA-561V & Shuttle Tile Status



- **SLA-561V TPS material performance issues**
 - MSL stagnation thermal ablation testing showed excellent stagnation heating performance up to 300 W/cm^2
 - However, arcjet tests at low heating ($90 - 150 \text{ W/cm}^2$), high shear, medium to high pressure and medium enthalpy conditions showed material failures
 - The material was dropped from consideration for CEV (7/07)
 - Mars Science Laboratory (MSL), which had baselined SLA-561V, switched their baseline material to PICA (11/07)
 - CEV testing of SLA-561V initially revealed the performance problems for SLA
 - If it were not for the PICA work by the TPS ADP, MSL would not have had an alternate material system available at a high enough TRL
- **Shuttle tile material performance issues**
 - Initial coupon testing of Shuttle tiles indicated excellent performance for BRI-18 (coated), LI-2200 (coated & uncoated)
 - Stagnation arcjet tests of gap/seam articles showed that at LEO heating and pressure conditions the material exhibits gap performance problems
 - Material was dropped from consideration for CEV heat shield utilization
- **Both candidate Block 1 materials have been eliminated from consideration for the heat shield**

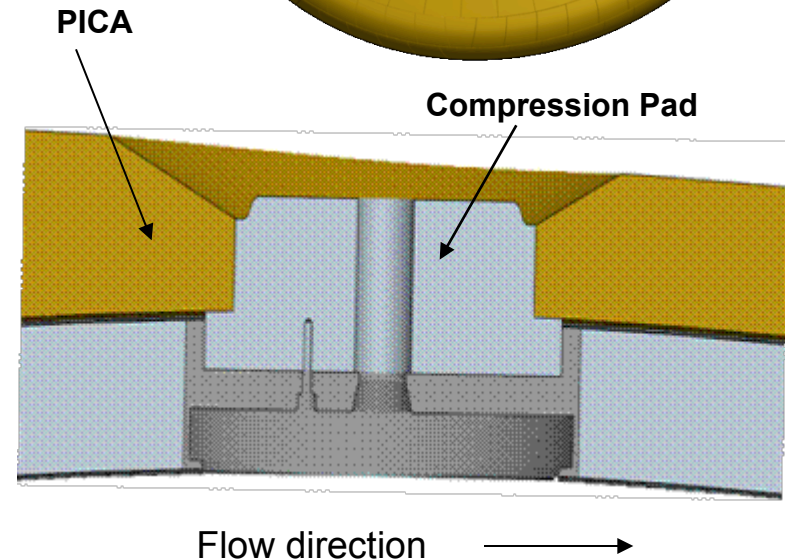
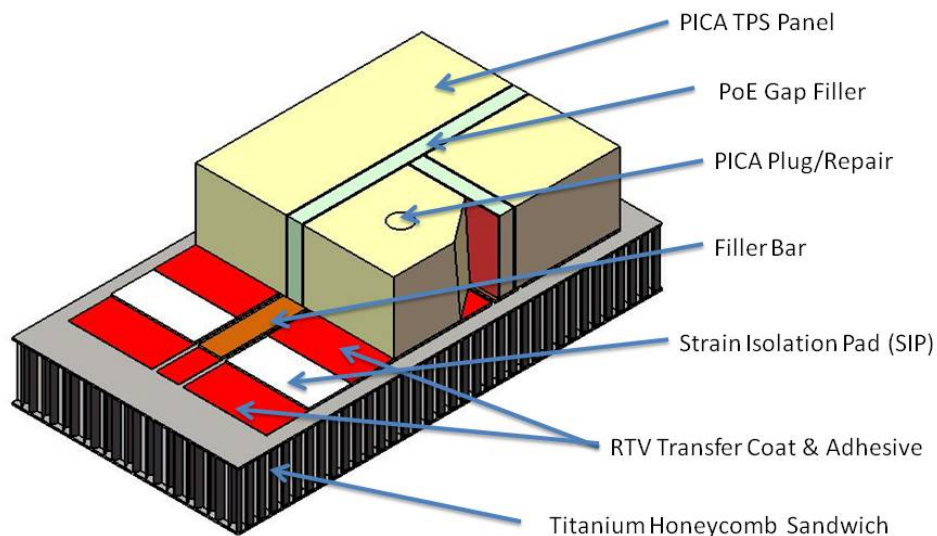
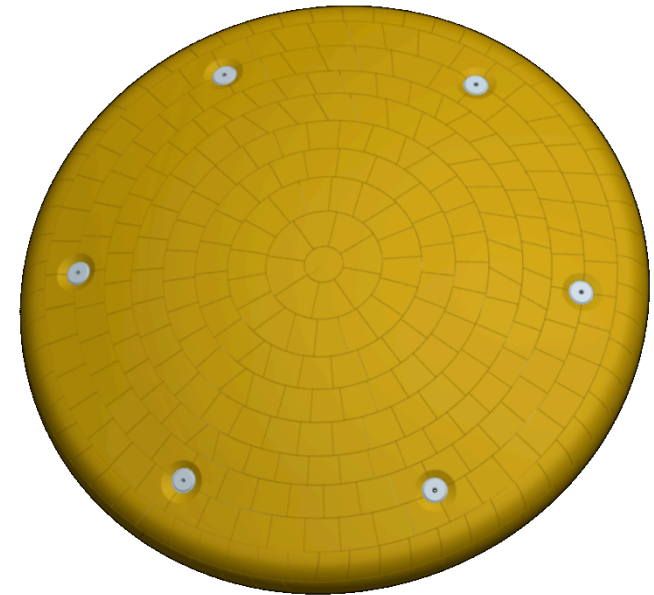


PICA System Description



• PICA (Phenolic Impregnated Carbon Ablator)

- Used successfully on Stardust – 12.8 km/sec (fastest Earth re-entry)
- Carbon fibers in loose matrix infiltrated w/ phenolic resin - 16 pcf virgin density
- PICA blocks sized to allow thermal-structural compliance (PICA is brittle)
- PICA blocks bounded to carrier structure using Shuttle heritage RTV-SIP-RTV
- Gap/Seam configuration not finalized
- Boeing/FMI contract initiated 8/06





PICA Development



- **Boeing / FMI production of PICA materials**
 - All PICA coupons / panels for NASA testing completed on schedule and within specs
 - Initially planned PICA material properties testing completed
 - PICA full-scale MDU completed 1 month ahead of schedule
- **Material properties & development of thermal-ablation model**
 - NASA V&V testing of PICA material properties and database complete
 - Completed updated 1-D & multi-dimensional PICA thermal response model
- **PICA and integrated performance testing**
 - Comprehensive acreage PICA stagnation and shear arcjet testing complete
 - PICA gap/seam configuration stagnation and shear arcjet testing complete
 - Comprehensive thermal-structural testing of acreage PICA and initial gap/seam configurations attached to flight-like carrier structure completed
 - Large article / bondline performance (arcjet), thermal gradient (solar tower), pyro-shock, main seal (arcjet), MMOD (arcjet) and integrated system (arcjet) testing complete
- **PICA block layout and gap/seam design**
 - Manufacturing limits of PICA is 42" x 24" x 10"
 - Deflection limits and PICA strengths indicate PICA flight panels limitations ~ 20"
 - Use of PICA on Edge examined as an alternative to RTV bonded gap/seam approach



Conflict of PICA Gap Design Requirements



Flight Loads Cause Relative Motion Between Tiles

Gap Closing Cases



Gap Opening Cases



Cold Soak



Hot Soak



Thermal and Pressure load induced deflections



Typical case of PICA on Edge Testing



Open Gaps Allow Flow into Gaps During Reentry



PICA on Edge Testing showing fencing

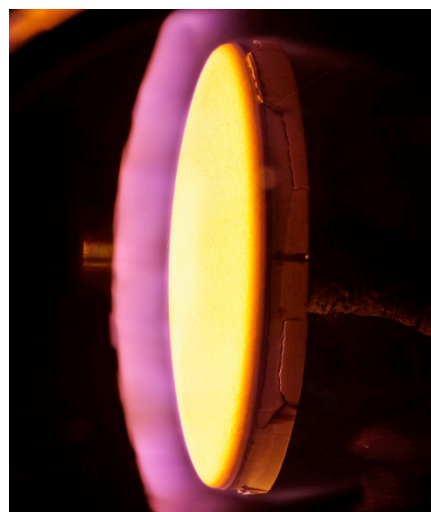
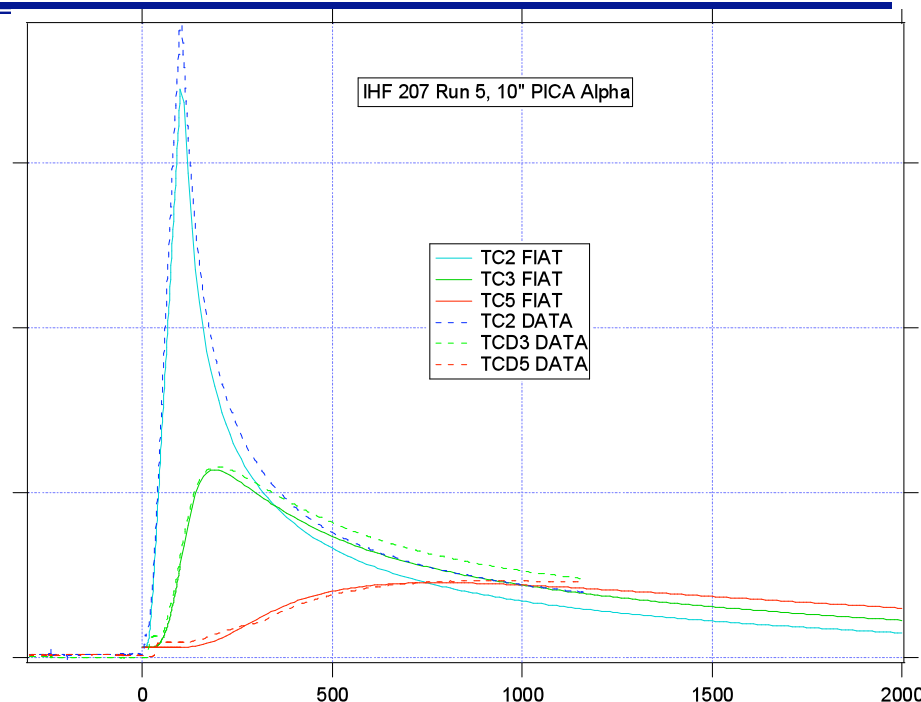
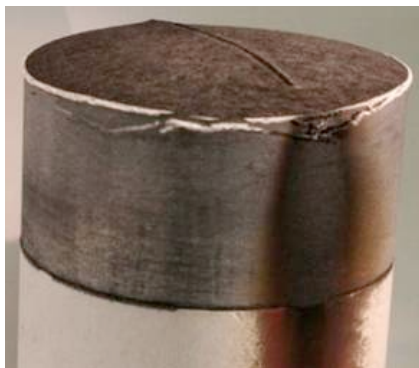


PICA MDU Manufacturing



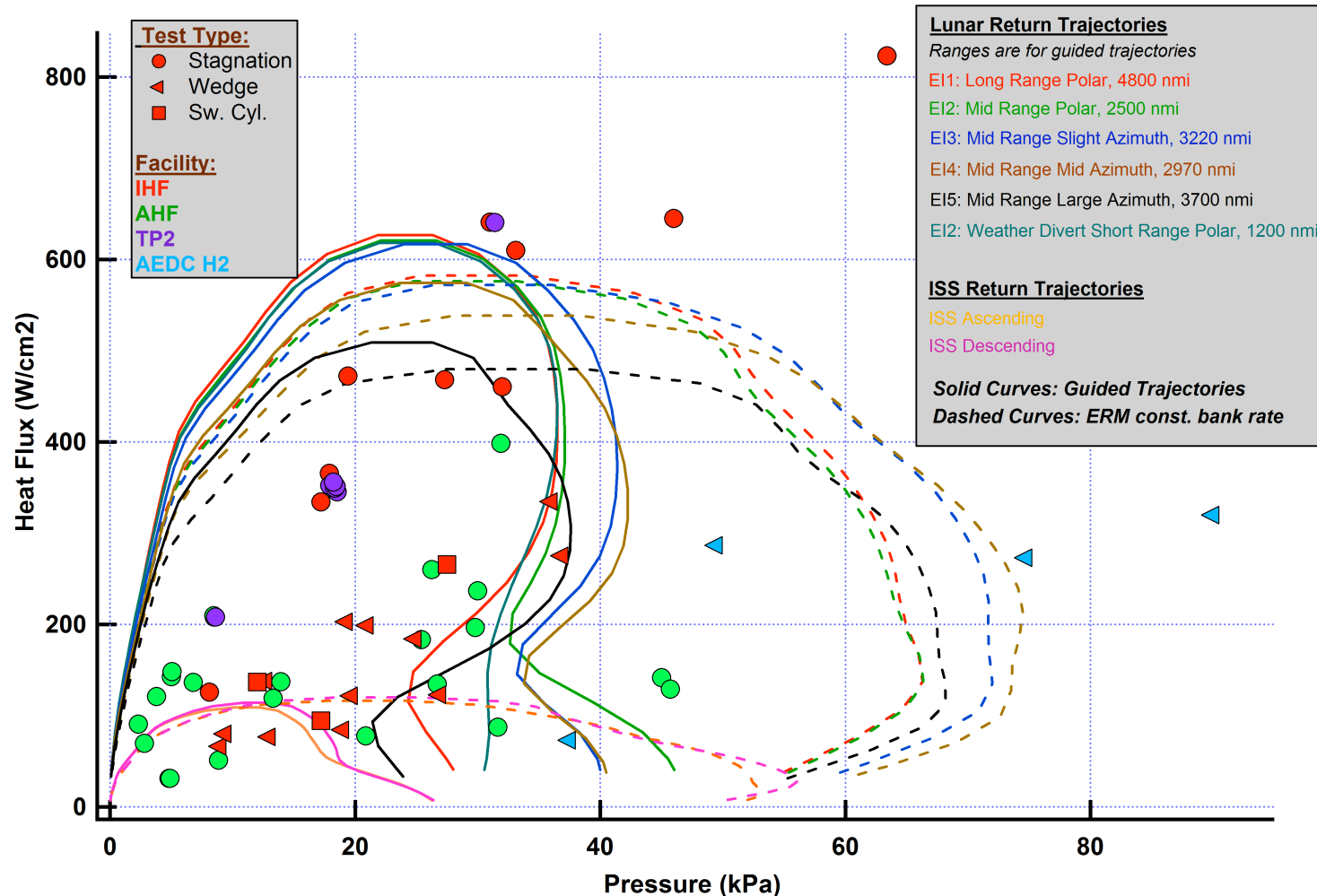


PIAC Arcjet Testing of Gaps/Seams & Large Articles





Flight Environments vs. Arcjet Test Environments: Heat Flux vs. Pressure



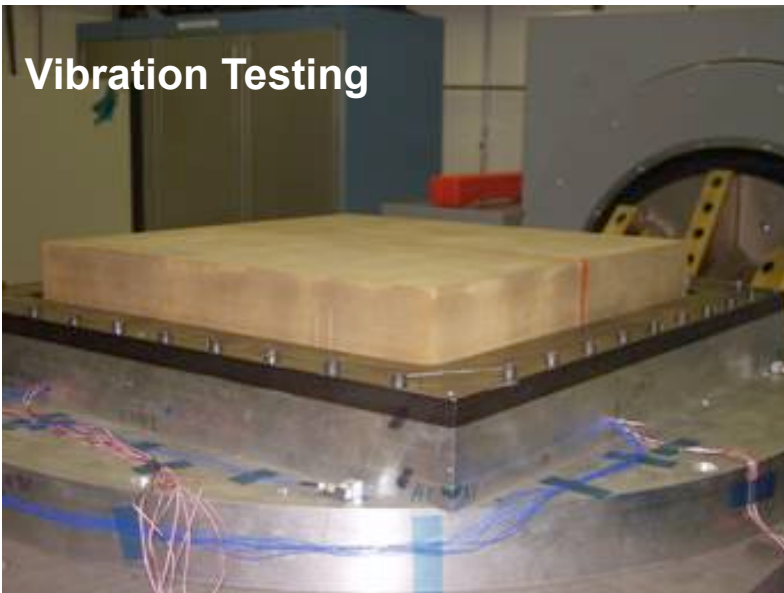
Does not include launch abort cases, one of which has stag pressures between 100–120 kPa, with corresponding heat fluxes between 80–200 W/cm².



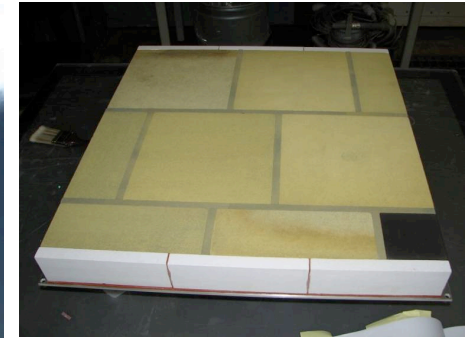
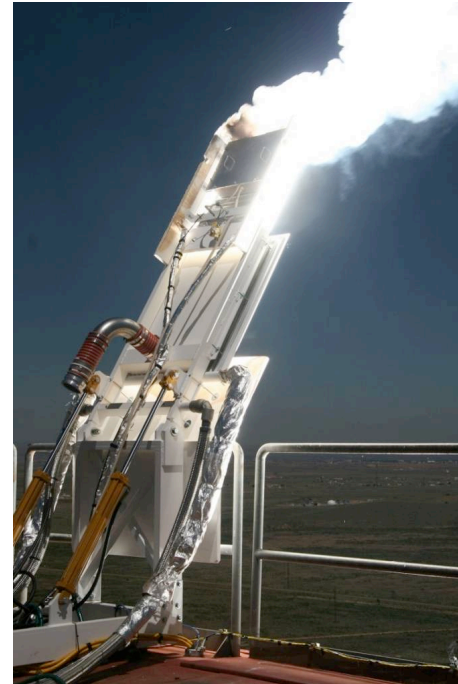
Mechanical & Solar Testing



Thermal Vacuum Testing



Vibration Testing



Solar Tower Test Facility

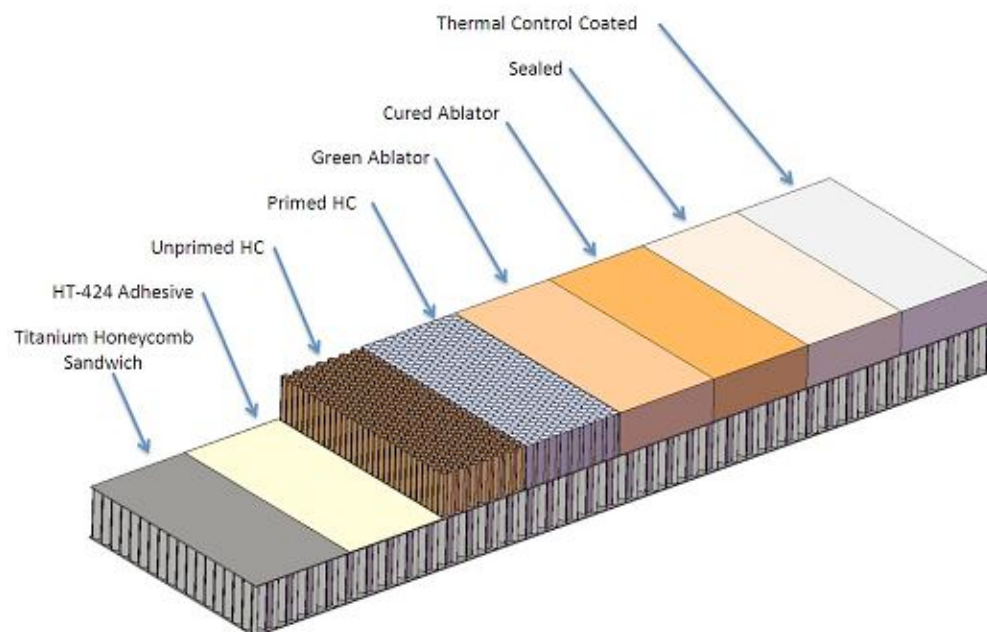


Avcoat System Description



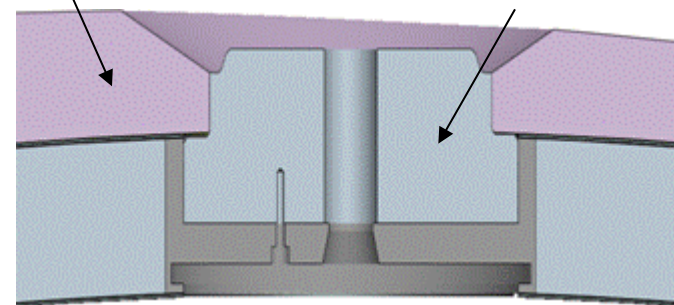
• AVCOAT 5026-39 HC/G Material

- Apollo heritage material
- Silica fibers with an epoxy-novalic resin filled in a fiberglass-phenolic honeycomb
- Large honeycomb gore sections bonded to carrier structure with HT-424
- Hand gunning of Avcoat ablator into H/C cells
- Textron contract initiated 5/07



Avcoat

Compression Pad



Flow direction →



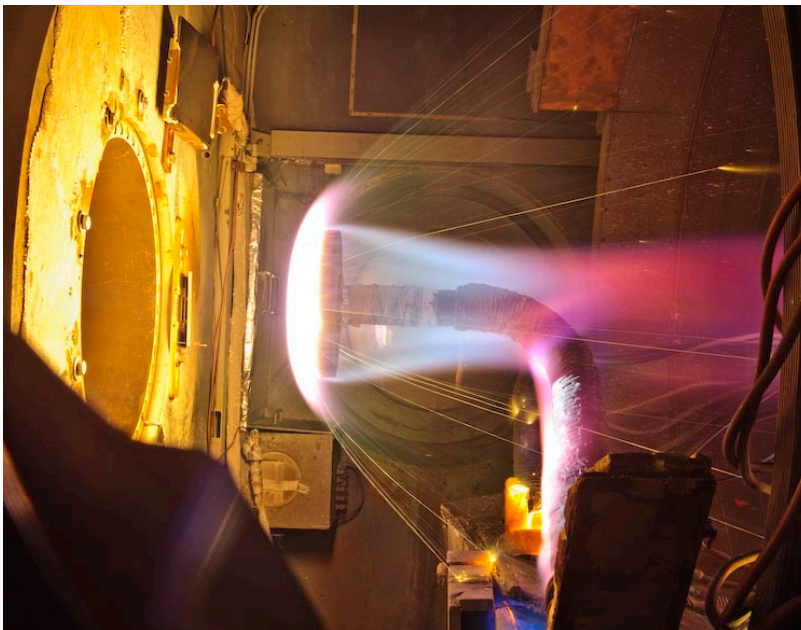
Avcoat Development



- **Textron production of Avcoat materials**
 - Initial coupon fabrication showed poor material quality & very slow production
 - Coupon quality & production rates improved to adequate and sustainable levels
 - Avcoat coupons and panels for NASA development testing complete
 - Avcoat full-scale (1/4) MDU completed
 - Initial testing of automated gunning study completed
- **Material properties & development of thermal-ablation model**
 - Initially planned Avcoat material properties testing complete
 - Resurrected the original 1-D Avcoat thermal ablation models (STAB, CMA)
 - Additional V&V testing of material properties for Avcoat completed
 - Thermal response models updated using new material property and arcjet data
- **Avcoat performance testing**
 - Development acreage Avcoat stagnation and shear arcjet testing completed
 - Development Avcoat seam arcjet testing completed
 - Thermal-structural testing of acreage Avcoat and seam configurations attached to flight-like carrier structure completed
 - Additional integrated thermal-structural, large article performance (arcjet), pyro-shock, and integrated system (arcjet) testing completed
- **Avcoat overall design and manufacturing**
 - Honeycomb gore sections limited to 40 inch wide
 - Flight heat shield manufacturing equipment installed: gunning booths, full-sized oven, tile-rotate table, digital x-ray and paint booth
 - Detailed thermal-structural analysis and design completed

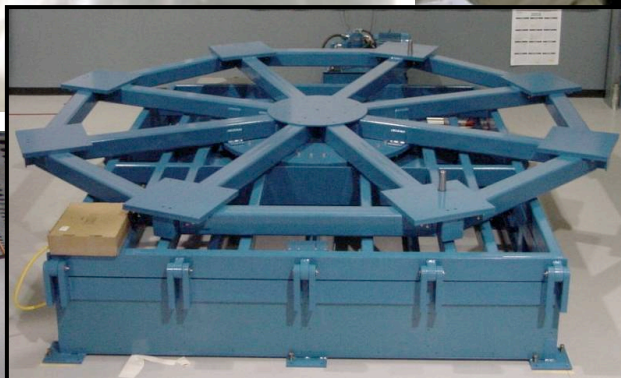
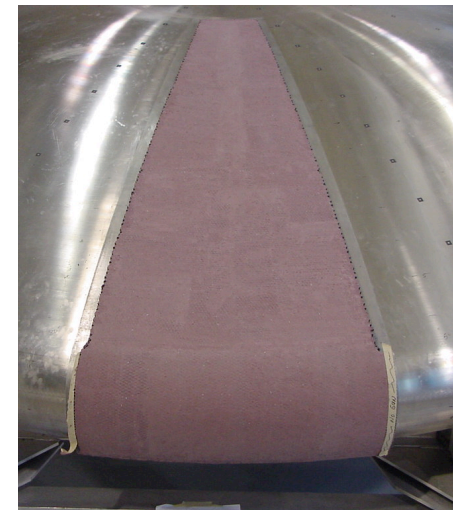


Avcoat Arcjet Testing – Heritage Testing, Seams and Large Articles





Avcoat Manufacturing Facility and MDU Production



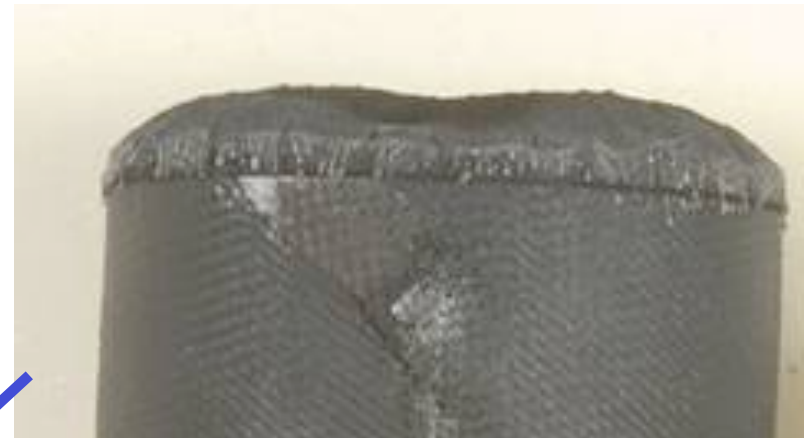
38735-A



Resurrected Avcoat Evolution



Phase 1 Avcoat
970 W/cm², 14 sec



"Spring '07" Avcoat
953 W/cm², 30 sec



Phase 2 Avcoat
1008 W/cm², 40 sec



Honeycomb Adhesion Problem



Early mechanical properties tensile testing revealed in-plane strength of less than half the quoted heritage Avcoat values. The problem was traced to adhesion failures between the Avcoat ablator and the honeycomb cell walls. After significant work by both Textron and the NASA TPS ADP team, a solution was found: an improved honeycomb cleaning process and an improved honeycomb primer process. The impact of this problem was significant delays in complete mechanical properties testing and production of thermal-structural integrated test units.



Adhesion Failure



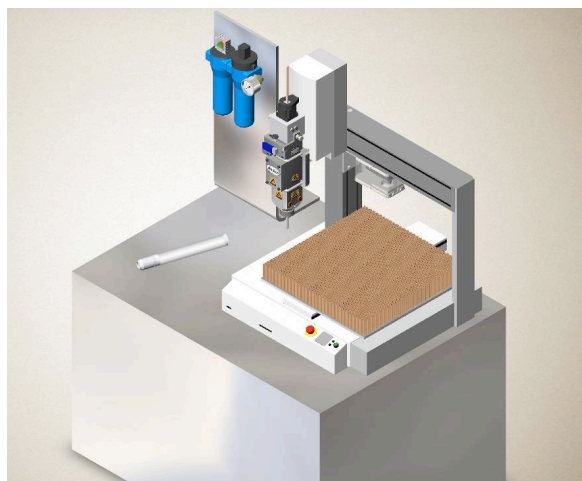
Adhesion Failure



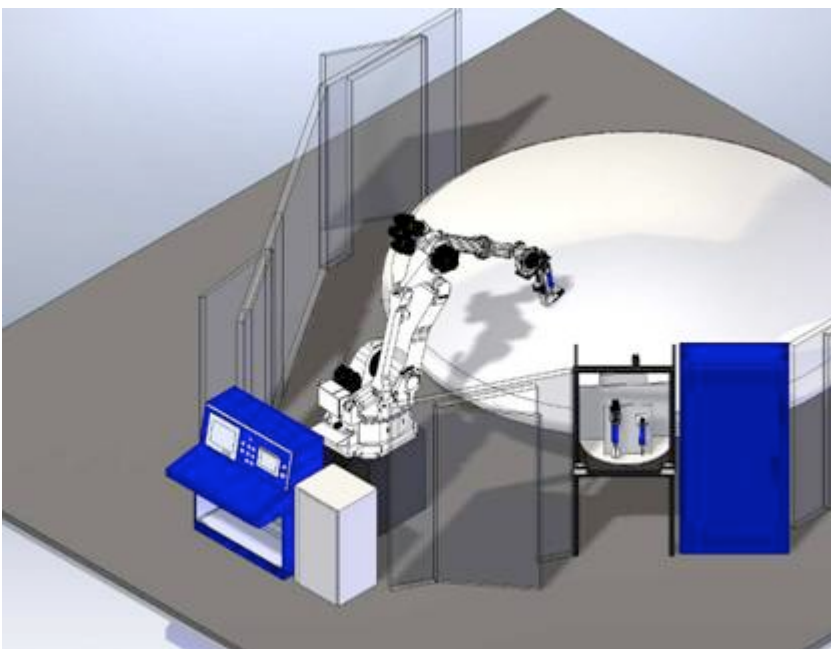
Standard Failure



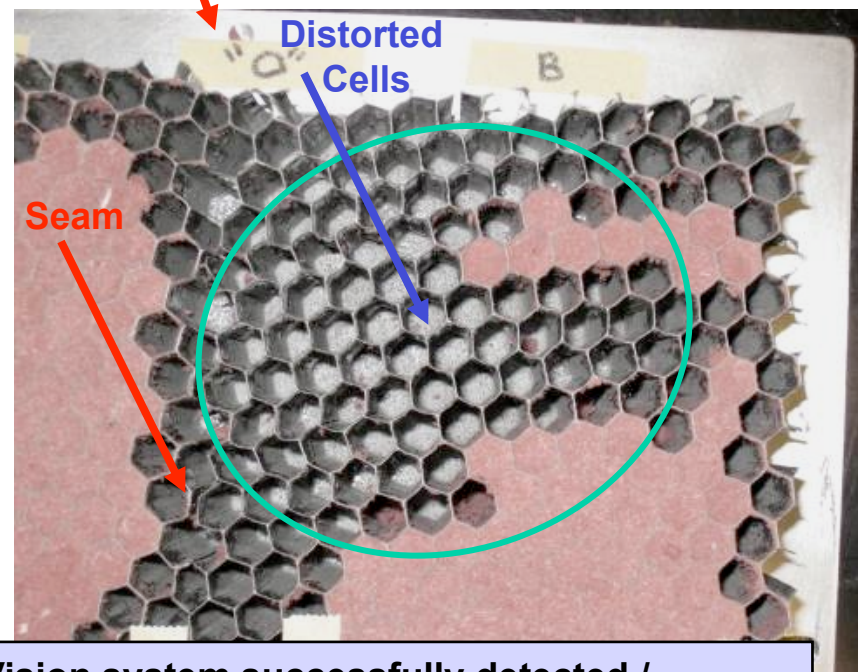
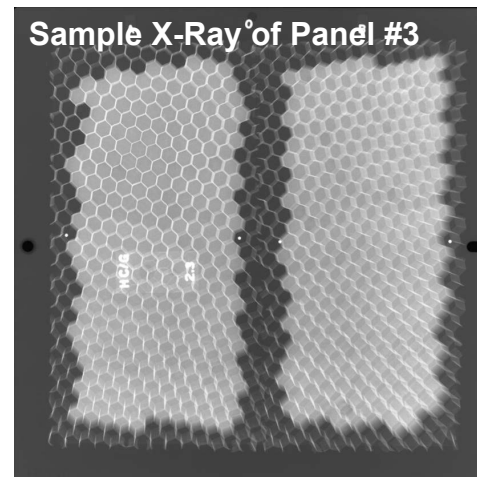
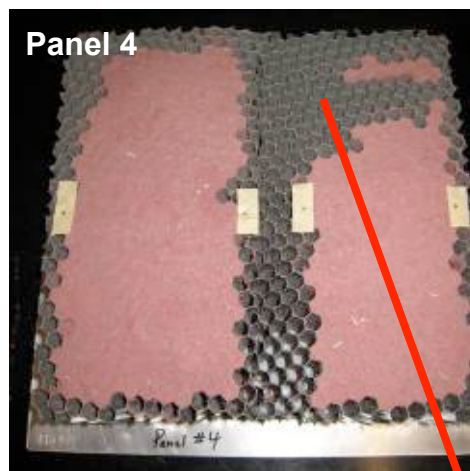
Avcoat Automated Gunning Study



4 Axis Cartesian Robot



Concept for final robotic manufacturing



Vision system successfully detected / avoided seams and defective cells



Final ORION Heat Shield Material Down Selection



- The TPS ADP matured two heat shield systems, Avcoat and PICA, to the extent that each was a viable solution for CEV
- Neither system had a clear show stopper development issue, however each still faced some residual technical risks:
 - The final PICA on Edge (PoE) gap/seam design for PICA required more significant thermal structural testing and analysis and the development of further manufacturing details
 - The Avcoat material properties database was not complete, more thermal-structural analysis & thermal performance testing was needed, and out-gassing impacts on properties/performance was needed
- The final down-select between PICA & Avcoat proceeded as planned (3/31/2009)
 - The TPS ADP performed a down selection panel meeting
 - Lockheed Martin provided an independent down selection recommendation
 - The Orion TPS SM provided an independent down selection recommendation
 - ***The unanimous down selection recommendation from all parties was Avcoat***
- The TPS ADP terminated as planned on 3/31/09



Down Selection Evaluation Metrics



1) Mass

- Ablator mass
- Integration mass (bonding, seams, coatings, etc.)
- Integrated heat shield mass
- Mass uncertainties estimates
- Mass threats and opportunities

2) Thermal Performance

- Arcjet performance over CEV entry environments
- "Cliffs" in material performance
- Off nominal thermal performance behavior (e.g. spallation, melt-flow, slumping, run-away recession)
- Acreage & integrated system thermal performance
- Response model maturity and material model-ability
- Ground to flight traceability uncertainty

3) Thermal Structural Performance

- Thermal structural robustness vs. load cases.
- Structural margins and sensitivities
- Maturity of supporting material property data
- Maturity of test and analysis techniques and results
- Understanding of failure modes

4) Life Cycle Costs

- DDT&E Qualification and acceptance costs
- Flight unit production costs.
- Raw materials processing and assembly costs
- Facilities, tooling, GSE and shipping costs
- Early flight test costs

5) Manufacturability Risk

- Part counts, raw material availability and supply chain
- Manufacturing robustness and complexity
- Availability of manufacturing infrastructure
- Availability of personnel with experience
- Manufacturing schedule risk
- Confidence and maturity of bond verification approach
- NDE and QA complexity and control
- Applicability of heritage and past performance

6) Certification Challenge

- Residual design and development
- NDE and QA maturity for certification
- TPS & integrated HS qualification & acceptance risk
- Completeness of HS V&V plan
- Need for dedicated early lunar flight test
- Schedule risk to complete qualification & acceptance

7) Reliability

- LOC reliability best estimate
- Confidence and uncertainties in reliability estimates
- Number and type of failure modes
- Design robustness

8) Technical Uncertainties and Concerns

- Residual technical risks & schedule readiness
- Maturity of analysis tools and methods
- Complexity of the design
- Other technical performance assessments



Key Lessons not to Forget:



- **Detailed TPS thermal performance requirements are difficult to specify:**
 - The n-vector (convective heat-flux, radiative heat-flux, pressure, enthalpy, shear, boundary layer properties, chemistry, etc.) of environments is complex
 - Environmental requirements change considerably during early vehicle design
 - Safety margins for environmental parameters based upon baseline and emergency entry modes reveals unexpected challenges
 - Developing high confidence thermal response model is difficult and time consuming
 - **Entry environments with high pressure and high shear, but moderate heat-flux and low enthalpy resulted in more unexpected material performance**
- **Comprehensive / extensive thermal testing beyond is necessary:**
 - The vehicle performance requirements tend to change during development
 - **Need to test for material performance “cliffs” – they exist**
 - Facility measurement capabilities have large uncertainties (+/-20 %)
 - Ground-to-flight traceability presents significant materials qualification challenges
 - **Large article and integrated system arcjet (and alternate thermal) testing should begin as soon as possible – coupon testing is not enough**
- **The capabilities of current ground test facilities are limited:**
 - There are only 3-4 applicable US arcjet test facilities today compared to 20-25 facilities during the Apollo era
 - The available facilities offer incomplete coverage (for CEV) and high downtime rates
 - The requirement for a flight test validation prior to manned flight is always a threat
 - **Panel-shear arcjet testing (with combined radiative heating) at moderate heat fluxes is a clearly missing capability for beyond LEO Earth return entries**



Key Lessons not to Forget:



- **The development of TPS materials is a careful balance between thermal performance and thermal-structural integrity**
 - Current large heat shield designs are either tiled systems (PICA) or a monolithic systems (Avcoat), with difficult thermal-structural constraints:
 - For an Orion PICA design, its in-plane vs. through-the-thickness stiffness and strength parameters resulted in the need for compliant gap/seam designs posing enormous difficulties
 - For an Orion Avcoat design, the monolithic design, combined with changes in thermal-structural material properties across cold (in-space) conditions through entry conditions results in challenging stress states
 - **Alternatives to address the difficulties: Very stiff carrier structure (MSL), or flexible / deployable TPS (e.g. IADs) – technology development needed**
 - Detailed thermal response must be understood for the integrated system not just for acreage TPS material
 - Penetrations and closeouts require significant work and are difficult to manage prior to PDR due to changing requirements



Key Lessons not to Forget:



- **Thermal-structural analysis and design proved very challenging:**
 - Statistical (A-basis) material properties do not exist for most TPS materials
 - Obtaining mechanical properties across a wide temperature range is challenging, and for TPS materials often produce large variations
 - TPS Mechanical failure modes are poorly understood & difficult to substantiate
 - Standard material property testing processes are problematic for TPS materials
 - Establishing an acceptable thermal-structural margins policy requires significant work
 - TPS materials are characterized by highly non-linear mechanical properties
 - Ablative TPS materials present additional challenges due to pyrolysis and ablation
 - **Developing a credible and validated series of FEM models for an integrated heat shield to assess various load cases requires significant experience / time**
 - Thermal-structural design and analysis based upon FEM is insufficient – combined environment testing, with thermal gradients and mechanical loads is needed
- **Restarting the manufacturing of previous TPS materials takes significant time and resources:**
 - Constituents usually require some changes due to changes in safety or precursor material availability (The TPS ADP held Rayon shirt Mondays to promote continued Rayon production)
 - Following a known recipe and process is often not enough, significant fabrication experience is required to produce quality and consistency
 - **Any of the material components (precursors, acreage materials, matrix – honeycomb, gap / seams, adhesives, and closeouts) can, and will pose difficulties**



Key Lessons not to Forget:



- **Manufacturing challenges occur at multiple levels:**
 - Producing consistency even at the coupon level proved challenging for some materials
 - **Every step in scale-up from coupon → panel → section → heat shield, can result in processing, consistency, thermal-structural, or integration difficulties**
 - Establishing necessary infrastructure requires significant time (~ 1.5 years)
 - Creating a volume production capability requires significant resources
- **Non Destructive Evaluation (NDE) and bond verification was problematic**
 - More time and effort are needed to develop digital x-ray based 3-D scanning
 - Alternate NDE methods need much more work
 - **Another area of technology development**
- **The current success of CEV TPS materials and heat shield designs does not represent a long term TPS development strategy**
 - Prior to the CEV TPS ADP effort, ablative TPS work was neglected for 40 years
 - The TPS ADP was an expensive, high risk, critical path approach to recover
 - Without the fortuitous timing of the CEV TPS ADP PICA heat shield effort, MSL would have had no TPS options to meet their Sep '09 launch window
 - **While PICA & Avcoat are viable for CEV, neither system is ideal – lower mass, increased robustness materials and systems were tantalizingly understood as possible but at too low of a TRL for CEV IOC**



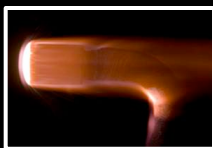
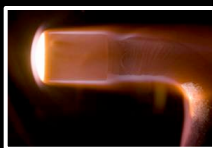
Conclusions Orion TPS ADP



- **The Orion Thermal Protection System (TPS) ADP was a 3 year \$150M effort to develop ablative TPS materials for the Orion crew capsule**
 - The ADP was motivated by the complete absence of ablative TPS materials to protect Orion for atmospheric re-entry
 - The TPS ADP pursued a competitive phased development strategy with succeeding rounds of development, testing and down selections
 - The Project raised the technology readiness level (TRL) of 8 different TPS materials from 5 different commercial vendors, eventual down selecting to a single material system for the Orion heat shield
- **In addition to providing a heat shield material and design for Orion on time and on budget, the Project accomplished the following:**
 - Re-invigorated a TPS industry that was in danger of collapse
 - Re-established a NASA competency able to respond to future TPS needs
 - Identified a potentially catastrophic problem with the planned MSL heat shield, and provided a viable, high TRL alternate heat shield material and design option within stringent schedule constraints
 - Transferred mature heat shield material and design options to the commercial space industry, including TPS technology information for the SpaceX Dragon capsule



Direct Results of the Orion TPS ADP



Competitive materials R&D resulted in multiple viable materials & systems



Avcoat: Selected for the Orion



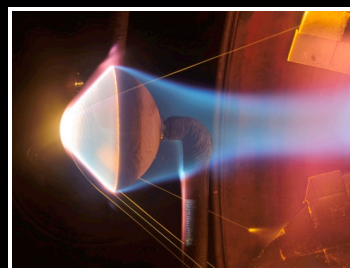
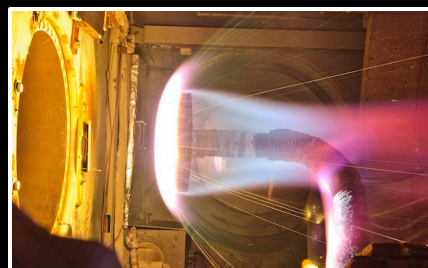
PICA: Selected for MSL & Dragon



TPS ADP Arcjet tests revealed catastrophic failure mode of initial MSL TPS



MSL shifts to a new TPS ADP developed TPS material



Large article arcjet testing demonstrated during TPS ADP is now a necessary TPS tool



- New NASA TPS experts
- Multiple TPS firms
- Large scale manufacturing
- TRL = 5-6 ablative TPS
- Promising new TPS concepts
- Technology transfer to commercial space industry